Fermilab, Feb 09

Dirac Dark Matter

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Outline

- Dark Matter and WIMPs
- KK, leptons, PAMELA
- Dirac, leptons, PAMELA
- Dirac Bino (SUSY strikes back)
- Summary

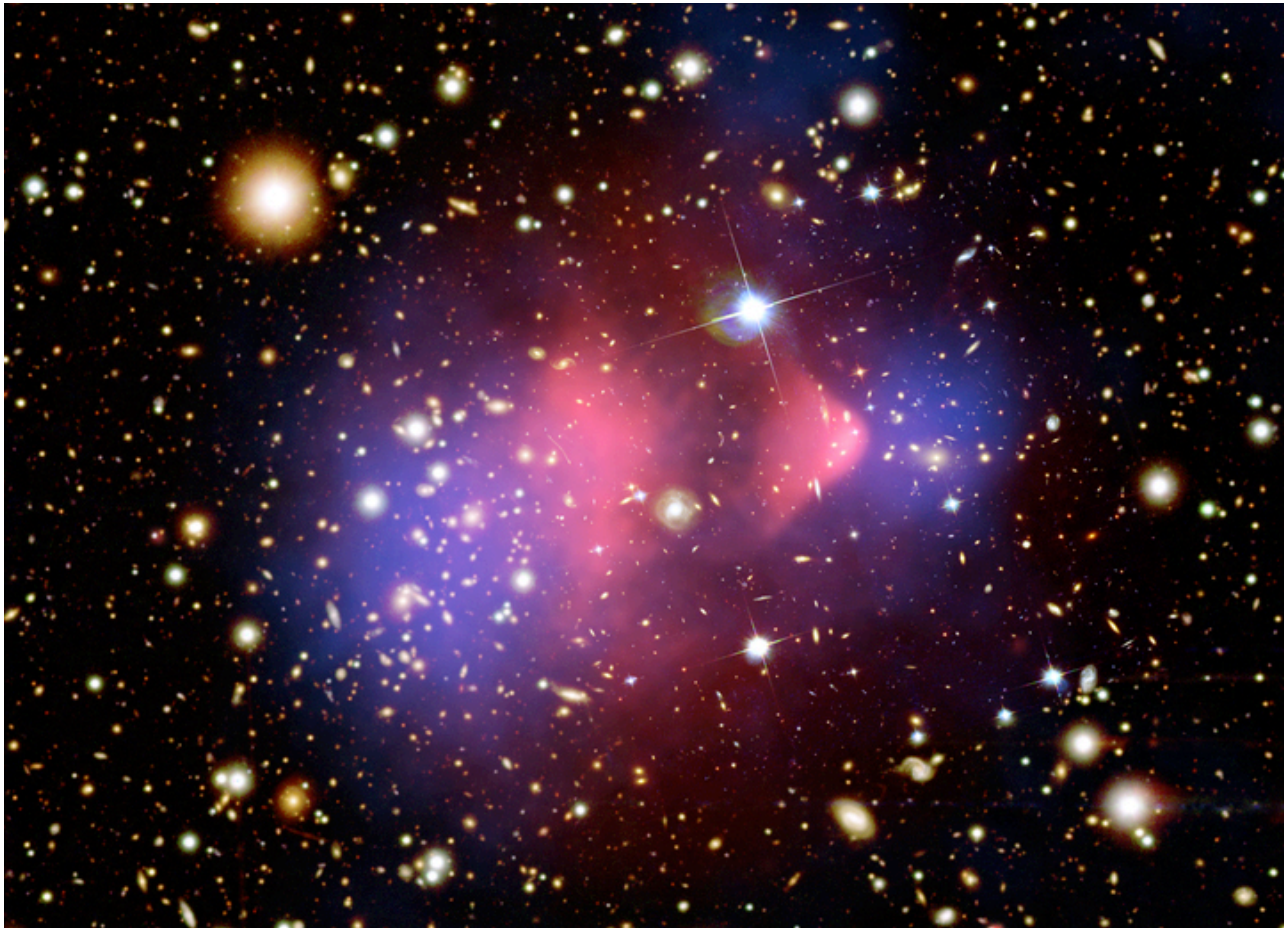
Dark Matter

Of all the puzzles in particle physics...

- $m^2_H \approx \Lambda^2$
- $CC \approx \Lambda^4$
- # generations
- quantum numbers
- ...

the existence of dark matter is "real Beyond-SM" that is not about aesthetics, fine-tuning, beauty...

Bullet Cluster



We don’t know:

Mass of Dark Matter

Composition of Dark Matter

Interactions of Dark Matter

We do know:

1) Dark matter is dark

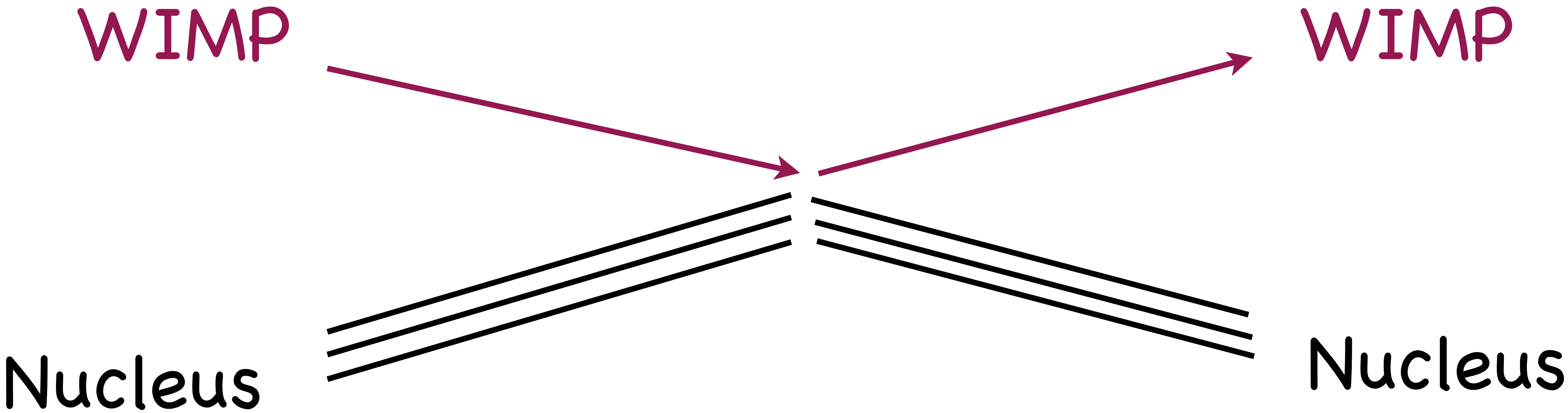
2) $\rho_{DM} \approx 5\ \rho_{matter}$ (averaging over Universe)

3) DM is cold

4) IF thermal freezeout, $\Omega h^2 \approx 0.1 \frac{1\ \text{pb}}{\langle \sigma v \rangle}$

WIMPs as Dark Matter

One of the most striking constraints

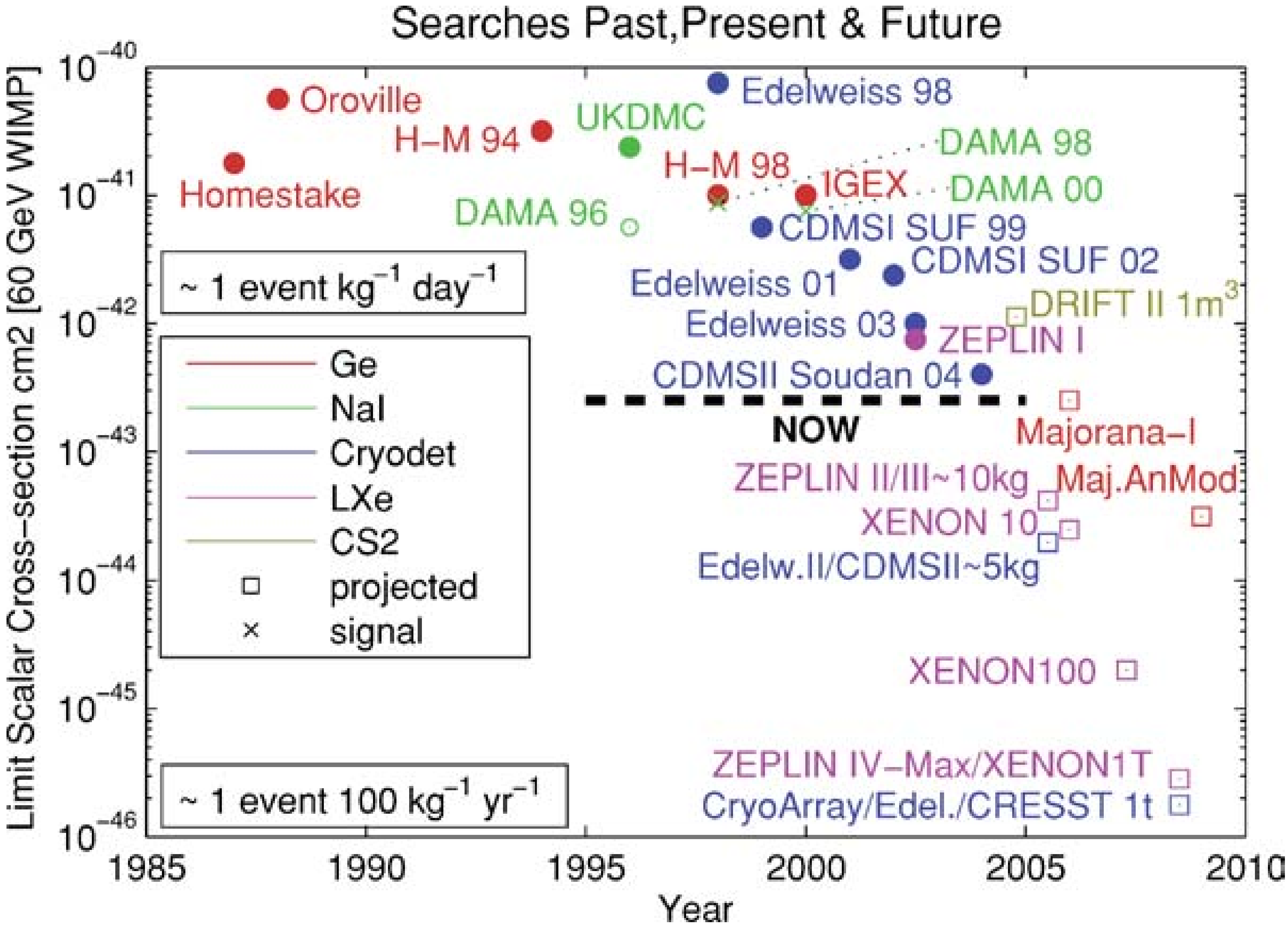


is direct detection.

If the WIMP-nucleon coupling is coherent w.r.t. mass

Effective nucleon cross section

$$\sigma_n \approx \frac{\sigma(\text{Nucleus})}{A^4}$$



Gaitskell 2004

Original (1980s) hope for WIMPs

Acquire

- mass from EWSB
- coupling to SM through EW interactions

e.g. fourth geneneration neutrino
that acquires Dirac mass with ν_{4R}

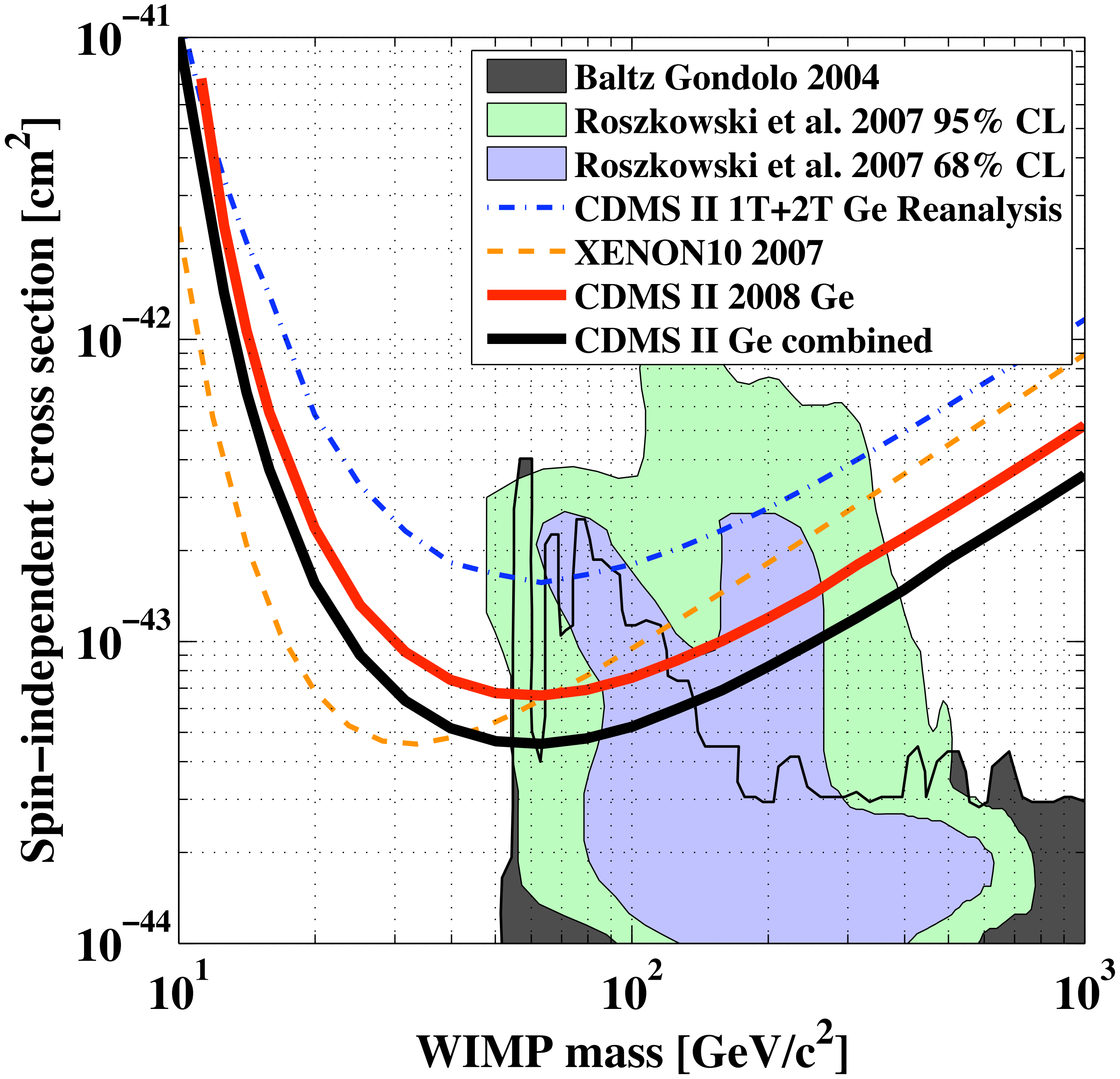
Such WIMPs have true Weak Interactions:

Vector interactions to SM with G_F strength:

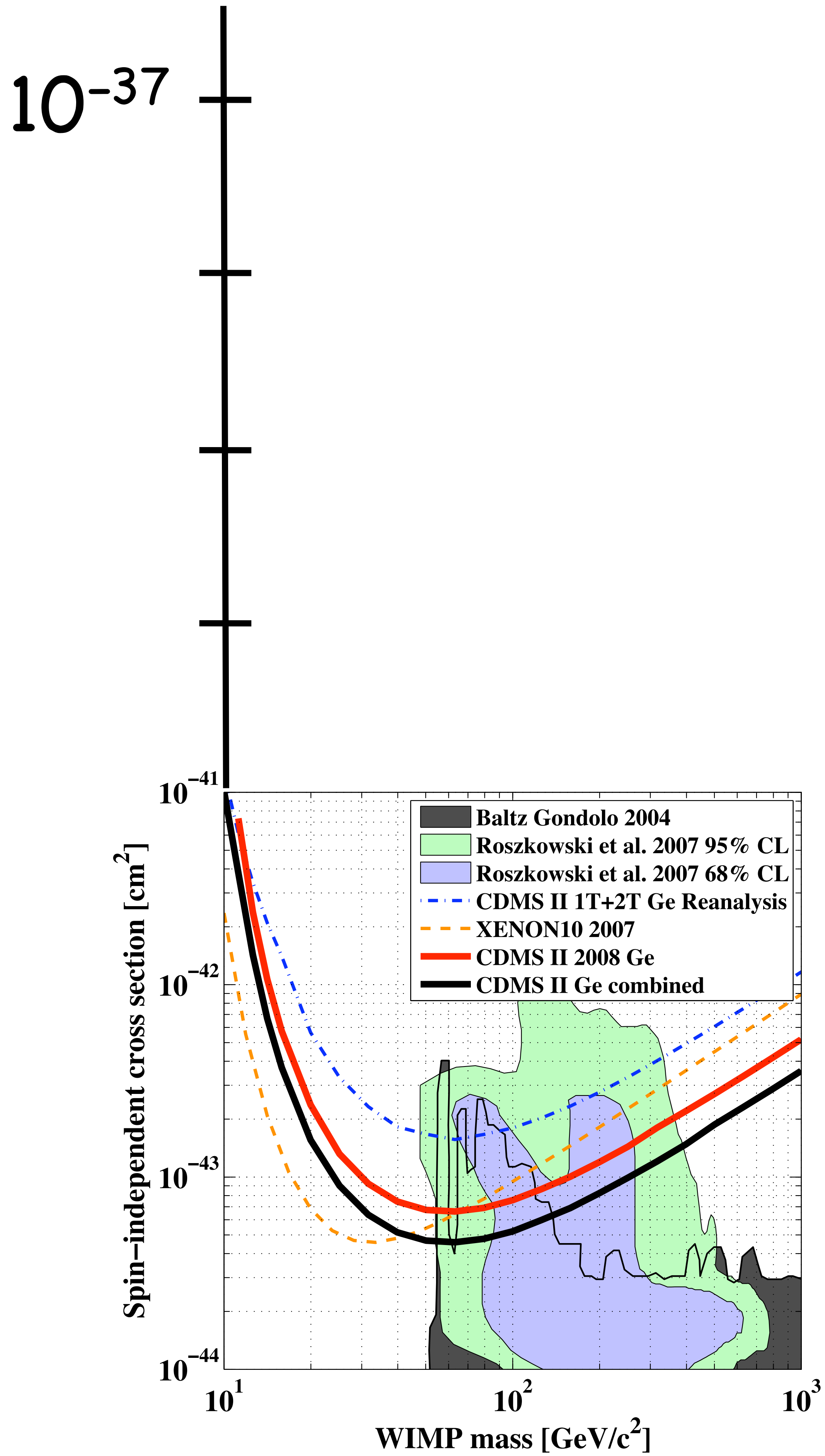
$$\frac{\bar{\nu}\,\gamma^{\mu}\,\nu\,\bar{q}\,\gamma_{\mu}\,q}{v^{2}_{246}}$$

Leads to WIMP-nucleon scattering cross section

$\sigma_n \approx 0.1$ pb! (for $\approx$ 100 GeV WIMP)



Completely Ruled Out by Direct Detection Bounds



10−37
10−41
10−42
10−43
10−44
10^1
10^2
10^3
Spin−independent cross section [cm²]
WIMP mass [GeV/c²]
Baltz Gondolo 2004
Roszkowski et al. 2007 95% CL
Roszkowski et al. 2007 68% CL
CDMS II 1T+2T Ge Reanalysis
XENON10 2007
CDMS II 2008 Ge
CDMS II Ge combined

Direct Detection Suggests:

Either:

- WIMPs couple to all SM fermions with sub-weak interaction strength (vector "g" $\lesssim$ 0.01; or Higgs exchange; or ...)

- WIMPs couple to leptons, not quarks (or gluons) Evades all direct detection constraints.

- Not thermal freezeout (forget about 1 pb scale)

- ...

Supersymmetric Dark Matter?

Mass from SUSY breaking; constraints from non-observation of SUSY

Coupling to SM matter is suppressed - Majorana fermion has no vector interactions

Viable, but has suppressed local galactic annihilation rate (relevant for recent hints...)

WIMPs Coupling Dominantly to Leptons

We already have examples...

"KK Dark Matter"

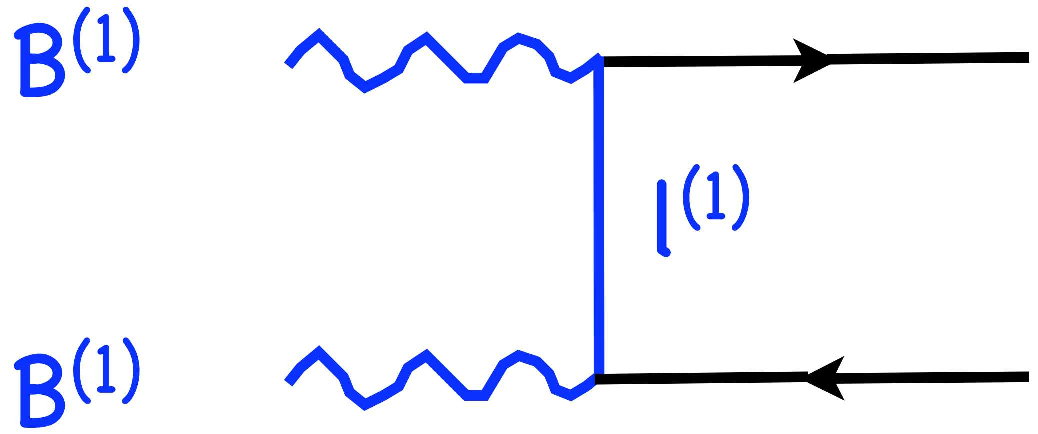
Appelquist
Cheng
Dobrescu

Dark matter is a Kaluza-Klein excitation of a Standard Model particle:

5d: first KK state of hypercharge $B^{(1)}$

Couples to hypercharge; hence dominant coupling to RH-lepton.

The annihilation rate:

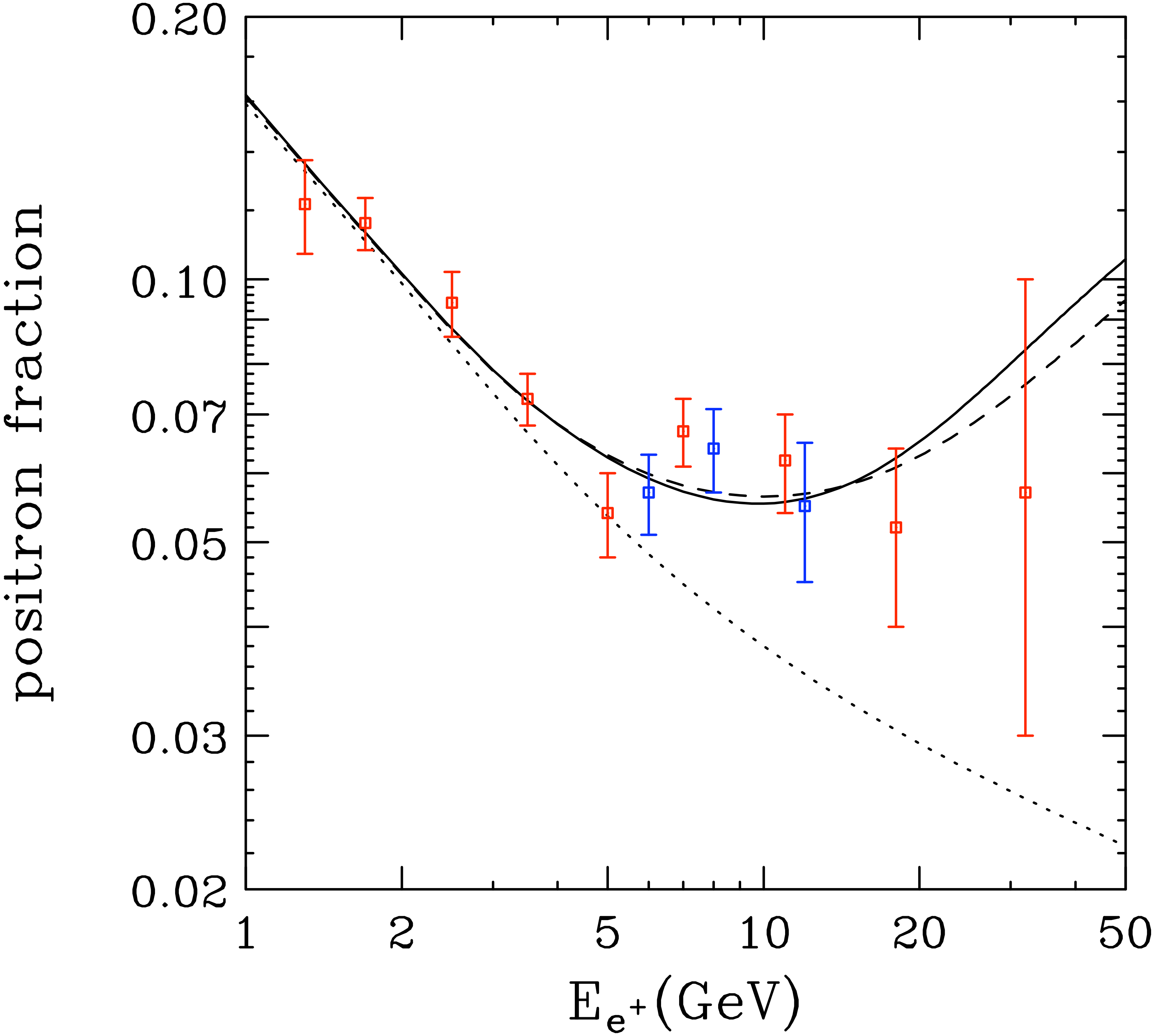


is not velocity-suppressed, leading to

$$\langle \sigma v \rangle_f \approx \frac{Y^4{}_f \, M^2{}_{B1}}{M^4{}_{l1}}$$

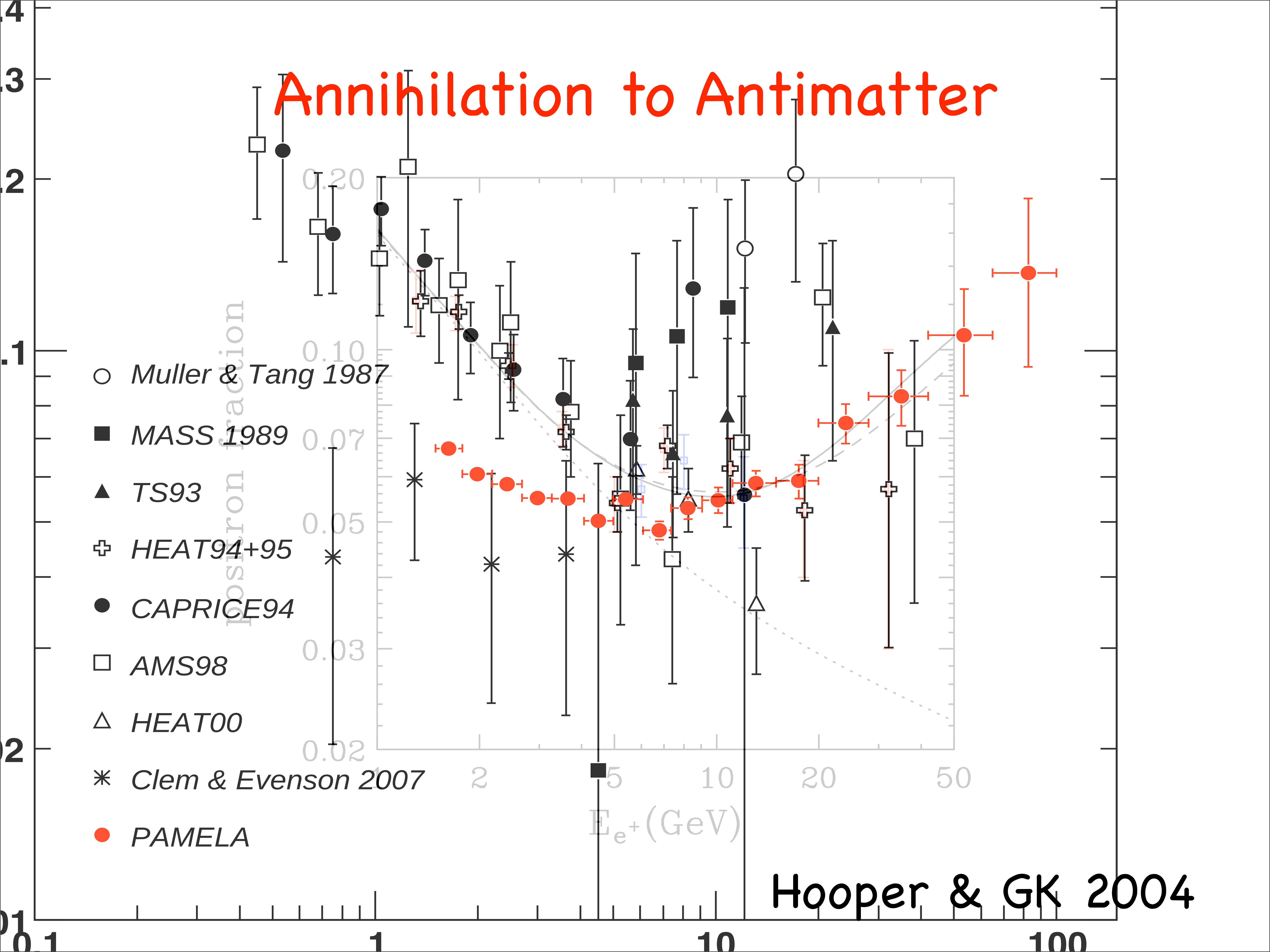
a modest hierarchy $M_{l1} < M_{q1}$ causes leptons to dominate, leading to an indirect detection signal:

Annihilation to Antimatter



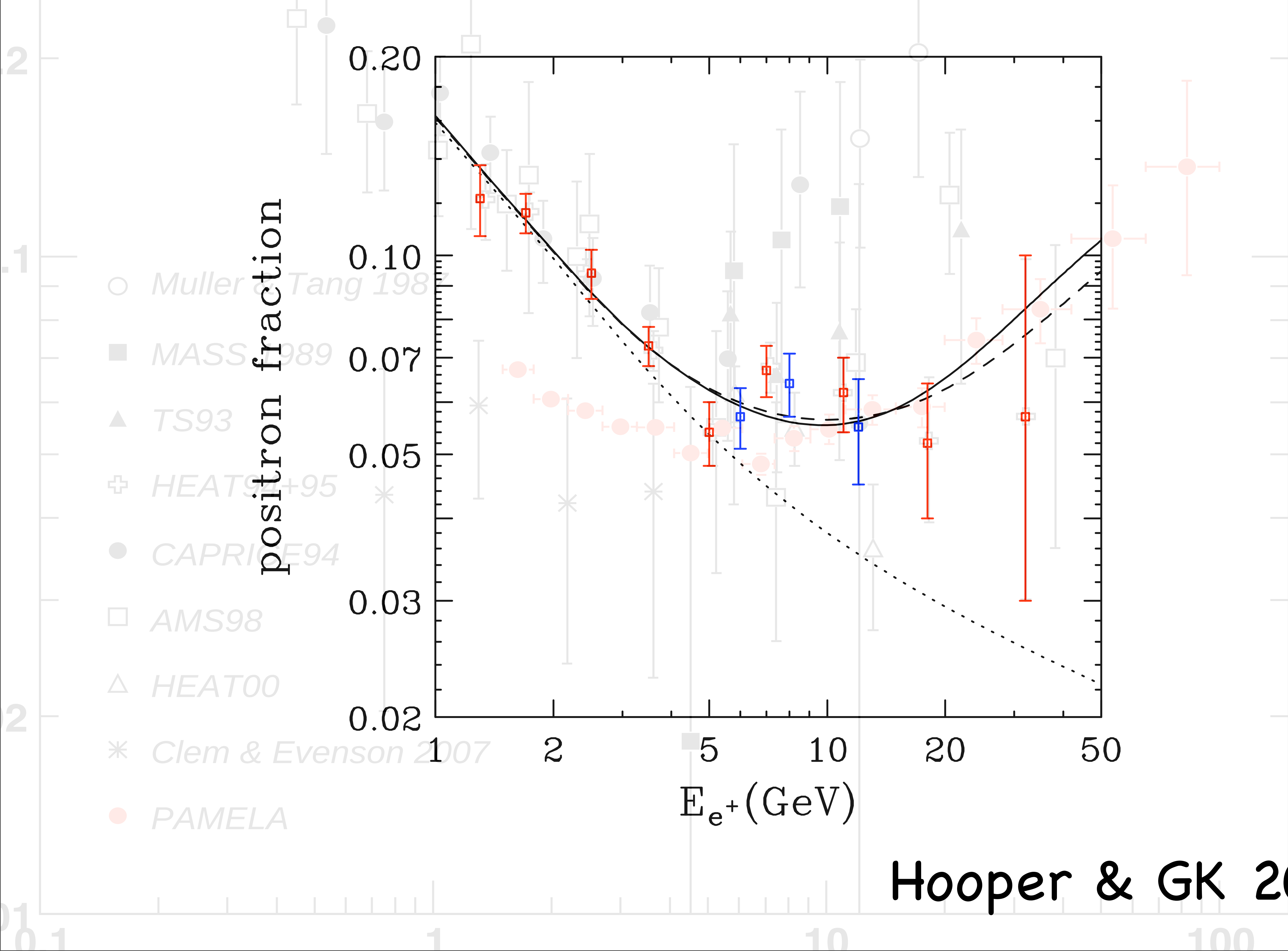
Hooper & GK 2004

Annihilation to Antimatter



Hooper & GK 2004

Annihilation to Antimatter



Hooper & GK 2004

Despite s-wave annihilation, with a large annihilation fraction to leptons...

- Tevatron + indirect bounds require $m_{B1} > 300\text{–}400$ GeV

- Matching thermal abundance $\Omega h^2 \approx 0.1$ requires $m_{B1} \gtrsim 600$ GeV

Implies local annihilation rate ≈ 20-200 x (1 pb)

to explain AMS/HEAT/PAMELA...
(large "boost factors")

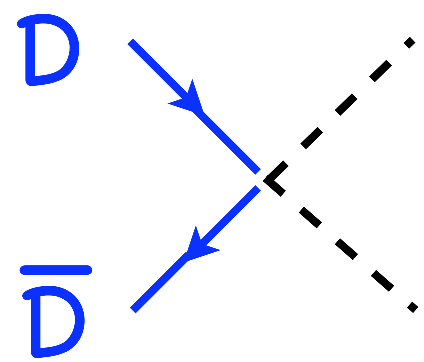
Dirac Fermion as Dark Matter

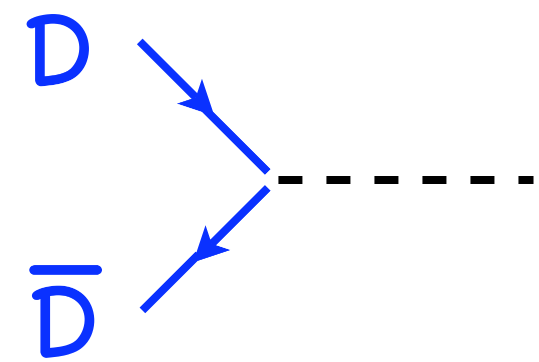
Dirac Fermion

- New Dirac fermion neutral under SM gauge group
- Global $U(1)_D$ conserved
- Interactions with SM through higher dimensional operators -- effective theory!

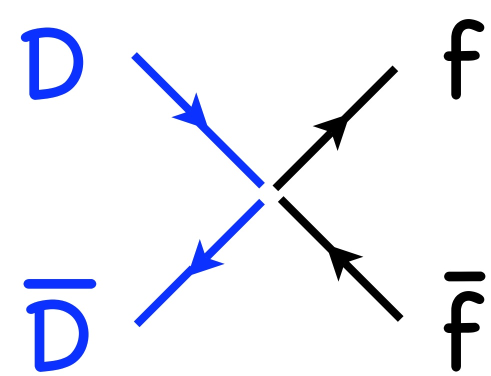
Higher Dimensional Operators

$$\frac{\bar{D}DH^{\dagger}H}{\Lambda} \longrightarrow$$





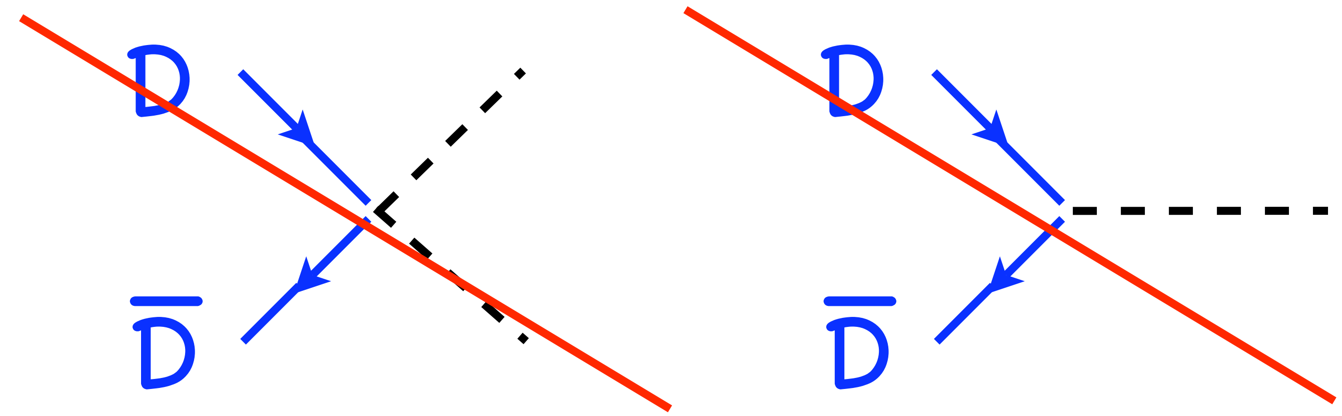
$$\frac{\bar{D}D\bar{f}f}{\Lambda^2} \longrightarrow$$



$1/\Lambda^2$

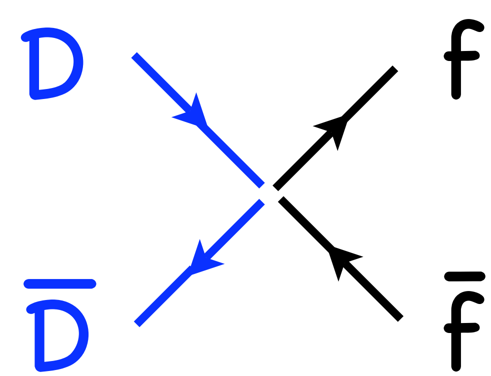
Higher Dimensional Operators

~~$\frac{\bar{D}DH^\dagger H}{\Lambda}$~~ $\longrightarrow$



ignore -- Higgs mass dependent
and leads to coupling to quarks, again
(operator absent in UV completion)

$\frac{\bar{D}D\bar{f}f}{\Lambda^2}$ $\longrightarrow$



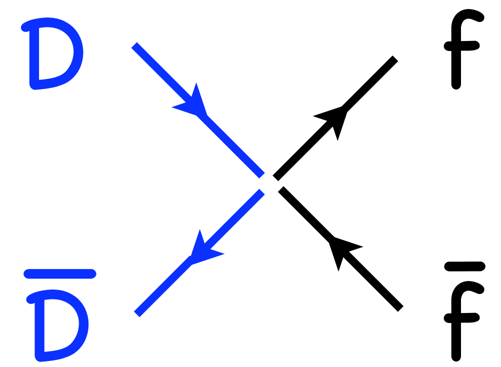
$1/\Lambda^2$

Thermally averaged cross section

$$\langle \sigma v \rangle = \sigma_0 + \sigma_2 v^2 + \ldots$$

Dirac fermion:

$$\langle \sigma v \rangle \sim M^2/\Lambda^4$$

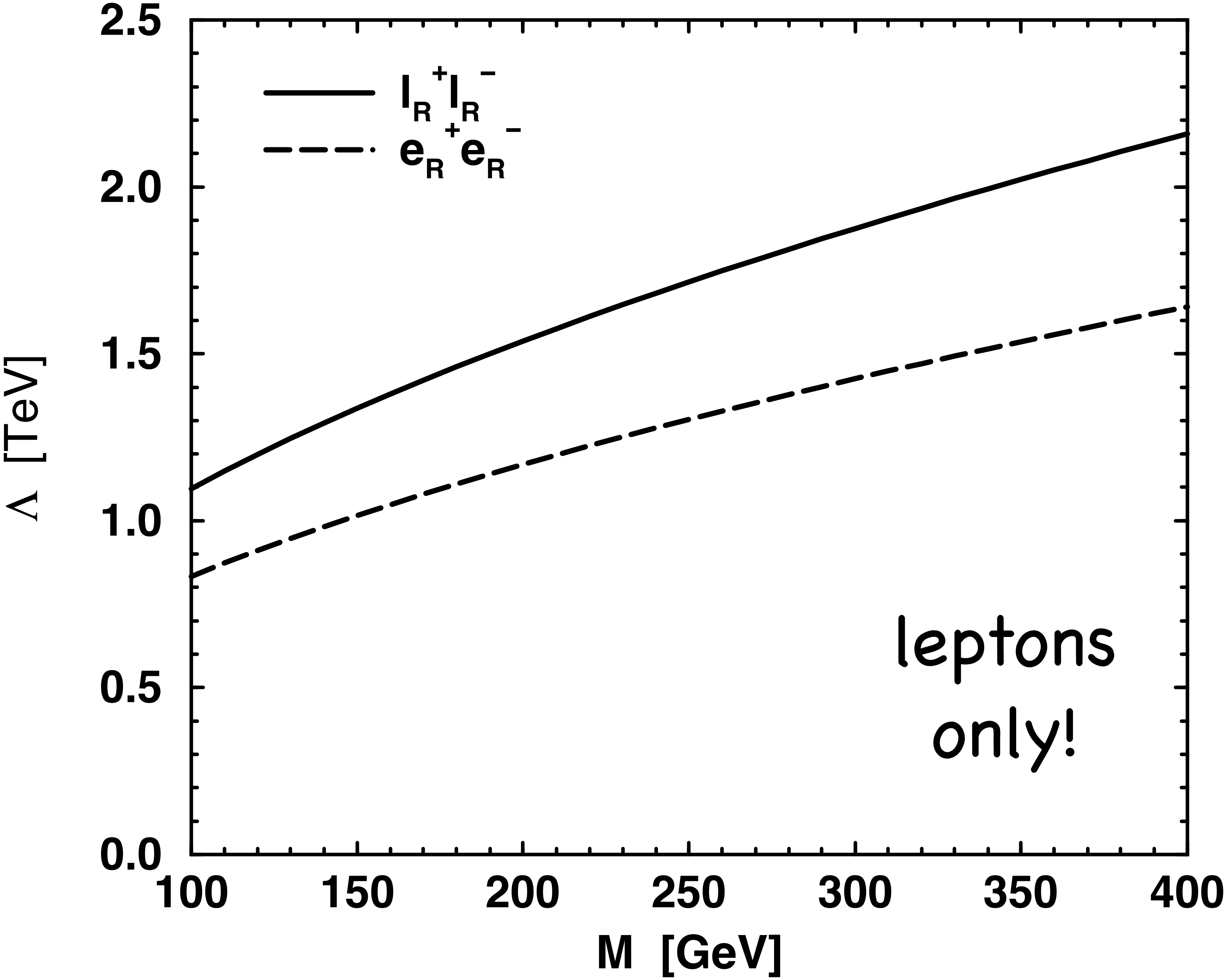


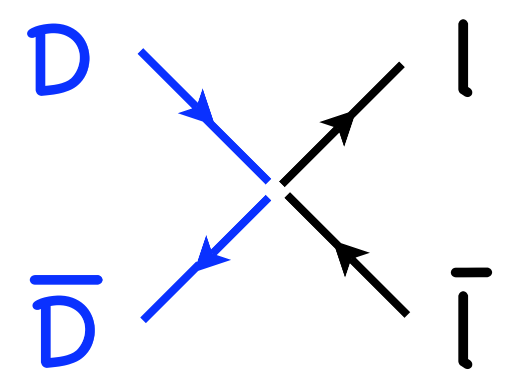
$1/\Lambda^2$

Consider coupling only to leptons
(and specifically, RH electrons)

Matching <σv> with thermal relic abundance:

$$\Omega h^2 \approx 0.1 \, (1 \text{ pb}/\langle \sigma v \rangle)$$





$1/\Lambda^2$

Harnik, GK

To make indirect DM annihilation predictions...

Astrophysics

Propagation:
- diffusion
- energy loss

Backgrounds:
- secondary production
- pulsars (neglected)

Abundance
- average density
- local clumpiness

Particle Physics

- annihilation rate
- annihilation channels

Effective theory allows:
- annihilation into e^+e^-,
- no other collider constraints ($M > 100$ GeV)!

Propagation

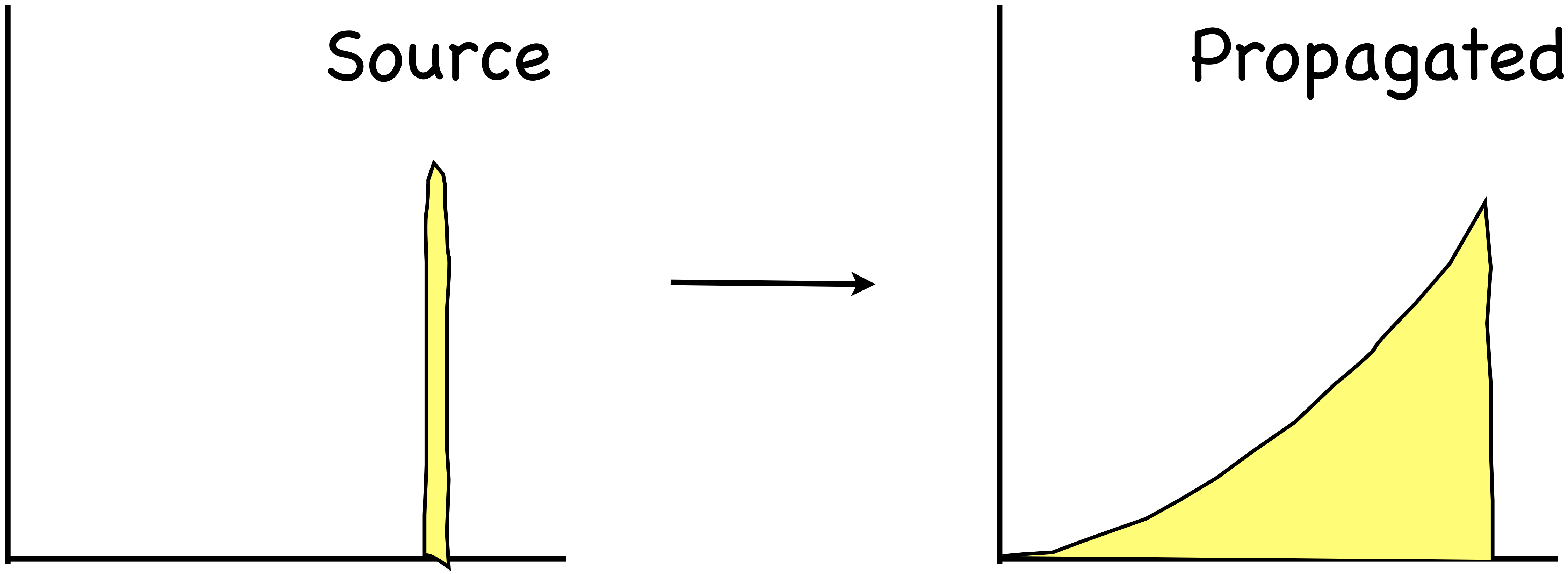
Diffusion: charged particles move in galactic magnetic field modeled as a random walk. Models (convection; reacceleration); and fit to observations (B/C ratio...)

Energy loss: light charged particles lose energy by synchrotron radiation & inverse Compton off starlight and CMB

We used "Galprop" [Moskolenko & Strong]. It requires as input, among other things:

- proton (nuclei) spectrum
- electron spectrum

For dark matter...



while diffusion randomizes the direction.

Typical scale for energy loss is ~ kpc,
i.e., our galactic neighborhood.

Secondary production

p $\longrightarrow$ p, nuclei

π^+-> ... e^+

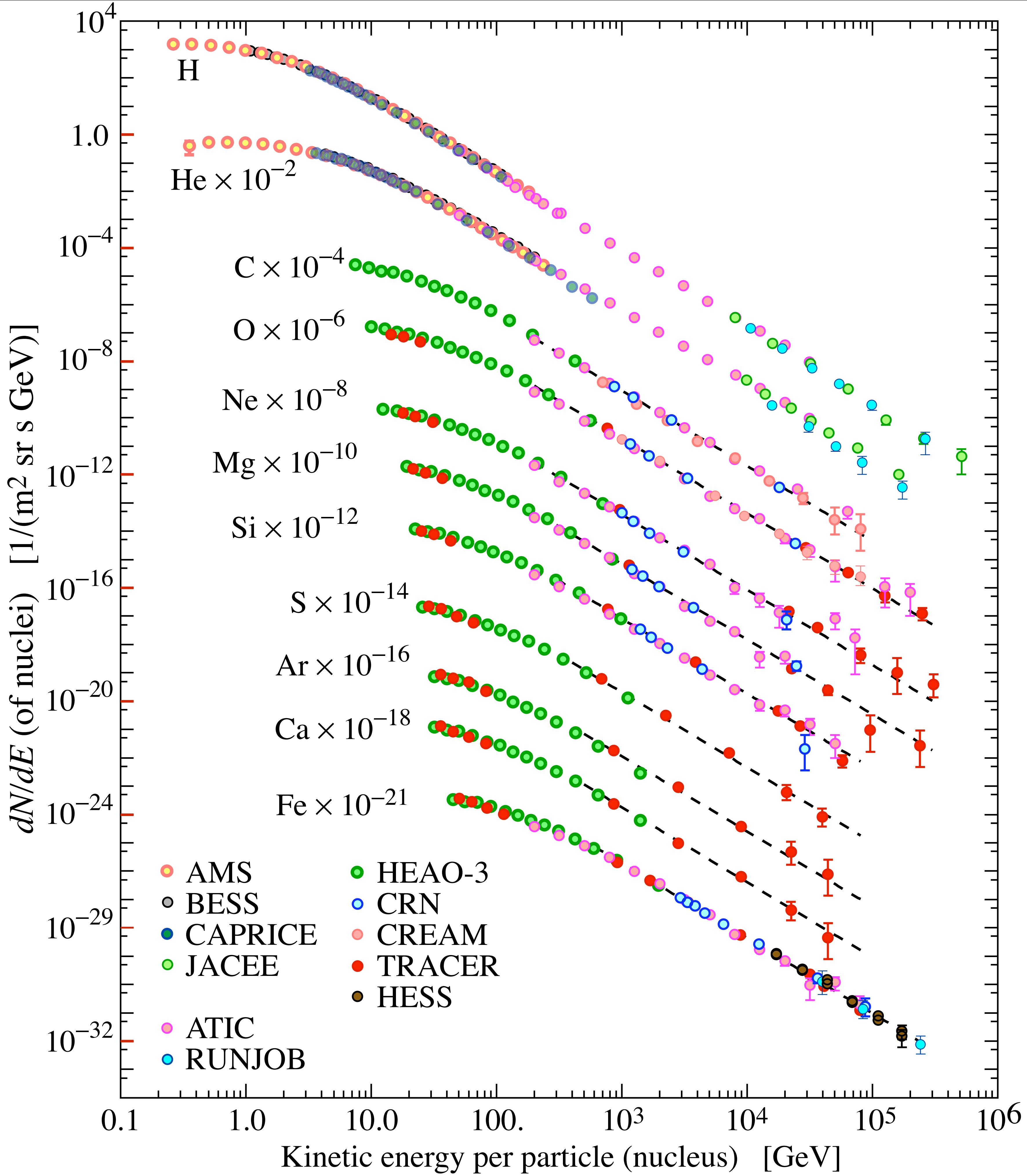
K^+->μ^+-> ...

->e^+

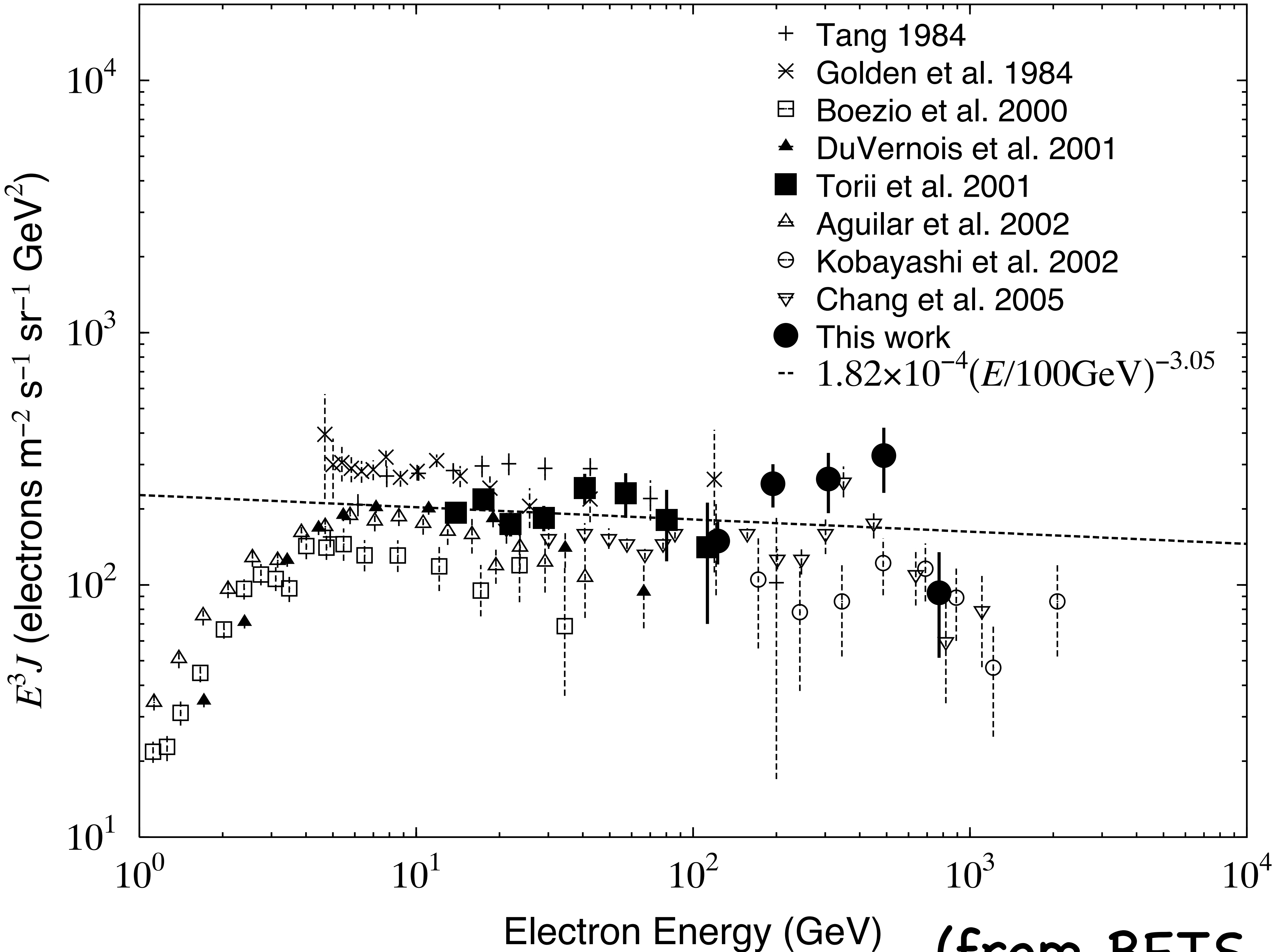
Position and antiproton spectrum determined entirely by:

input proton spectrum + propagation

Observed Nuclei Spectrum:

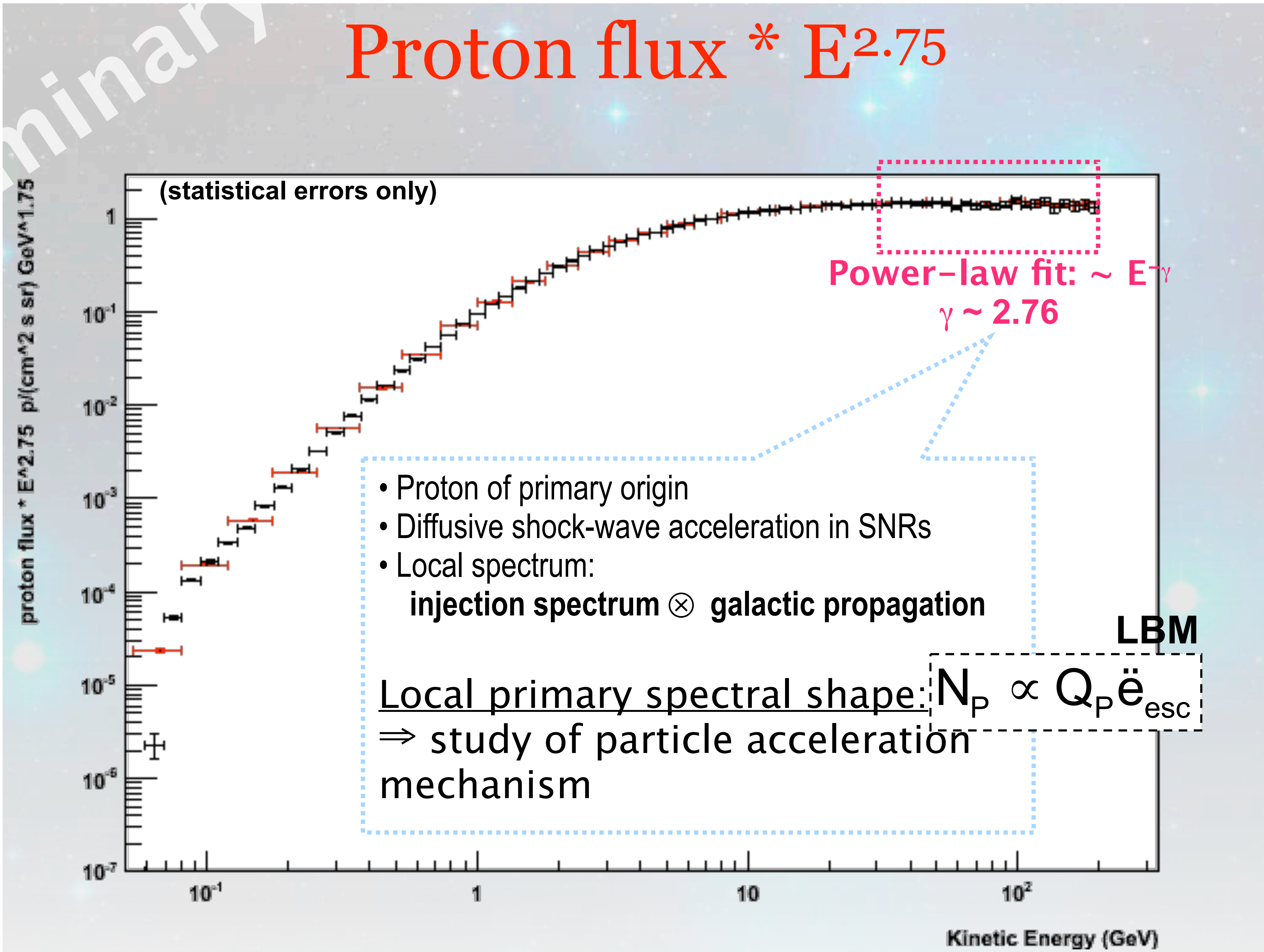


Observed ($e^- + e^+$) flux



(from BETS paper)

PAMELA proton data



PAMELA ($e^+ + e^-$) flux data

(no data yet...)

This means, in principle, the positron ratio excess could be...

An excess in positrons **OR** A deficit in electrons

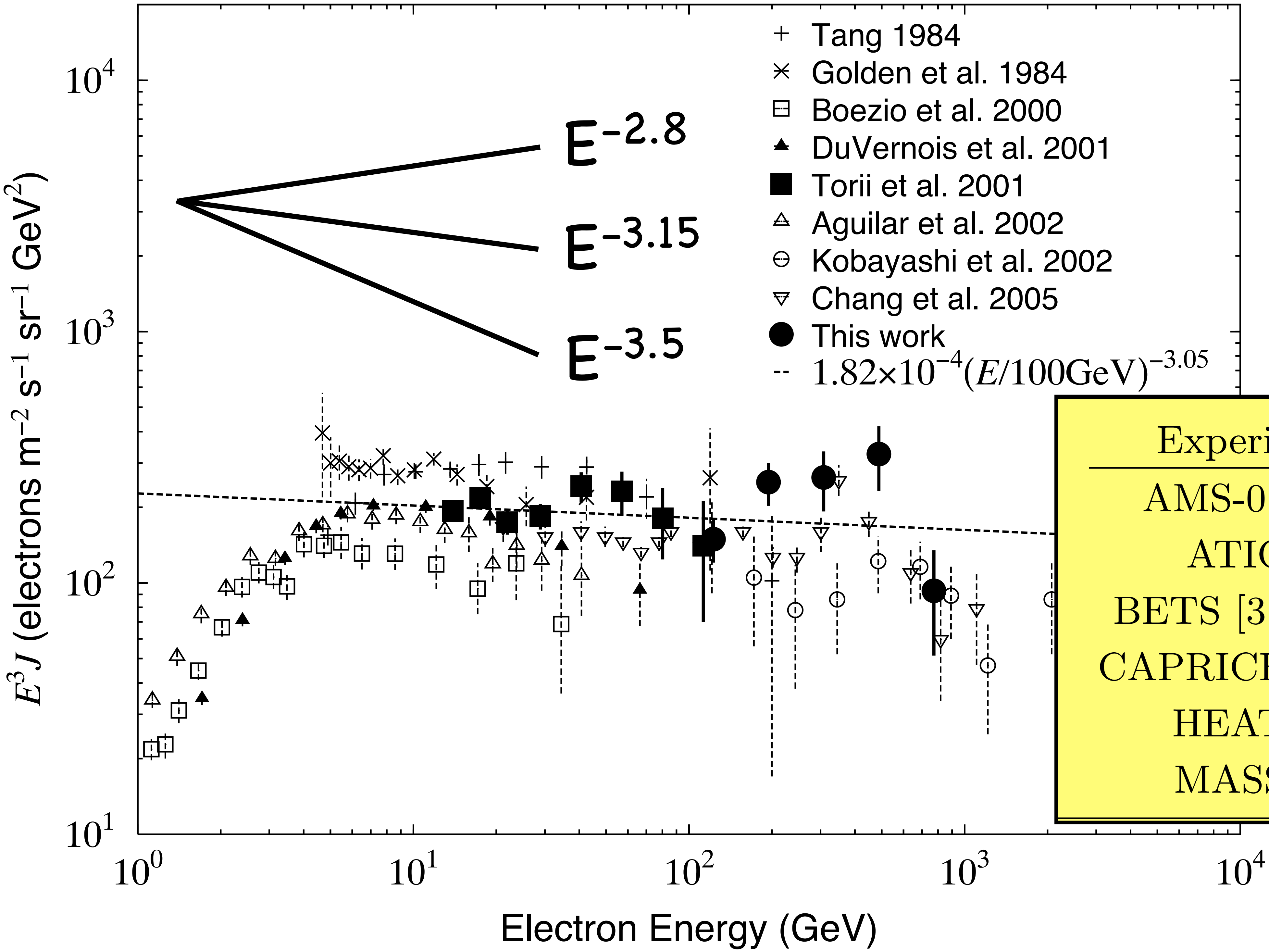
(rumored data suggests not deficit)

Our approach (Oct 08)...

Use existing electron data from other experiments to determine the shape of electron flux.

Use absolute positron flux derived from secondary production (protons smashing protons), and normalize electron flux using PAMELA ratio at 5 GeV

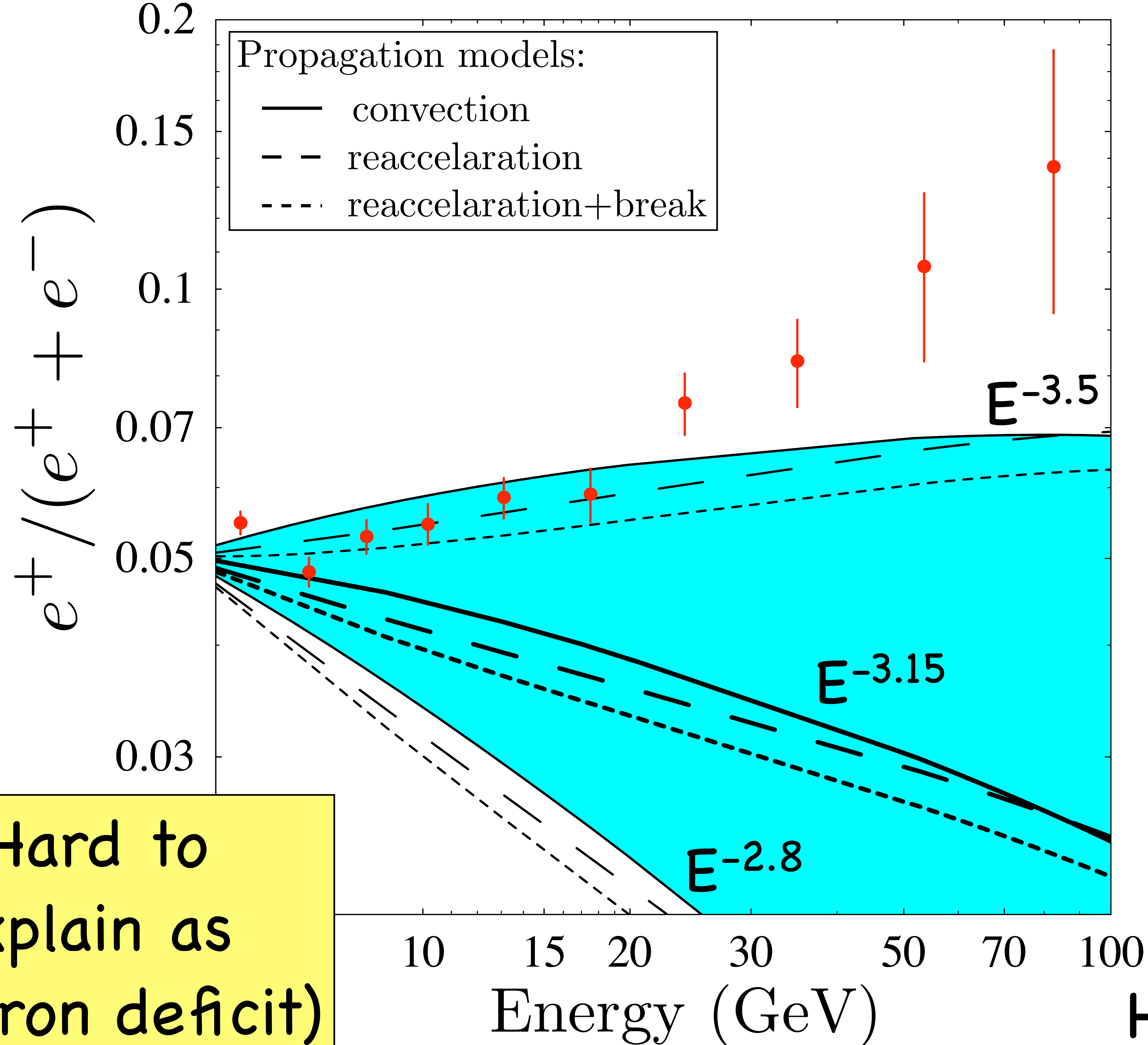
Use existing electron data (5-100 GeV only)



Experiment	power law index α
AMS-01 [29]	3.15 ± 0.04
ATIC [30]	3.14 ± 0.08
BETS [31, 32]	3.05 ± 0.05
CAPRICE [33]	3.47 ± 0.34
HEAT [34]	2.82 ± 0.16
MASS [35]	2.89 ± 0.10

Interpretation: $E^{-2.8} > \Phi(e) > E^{-3.5}$

Secondary production ONLY (no dark matter):



PAMELA ratio data

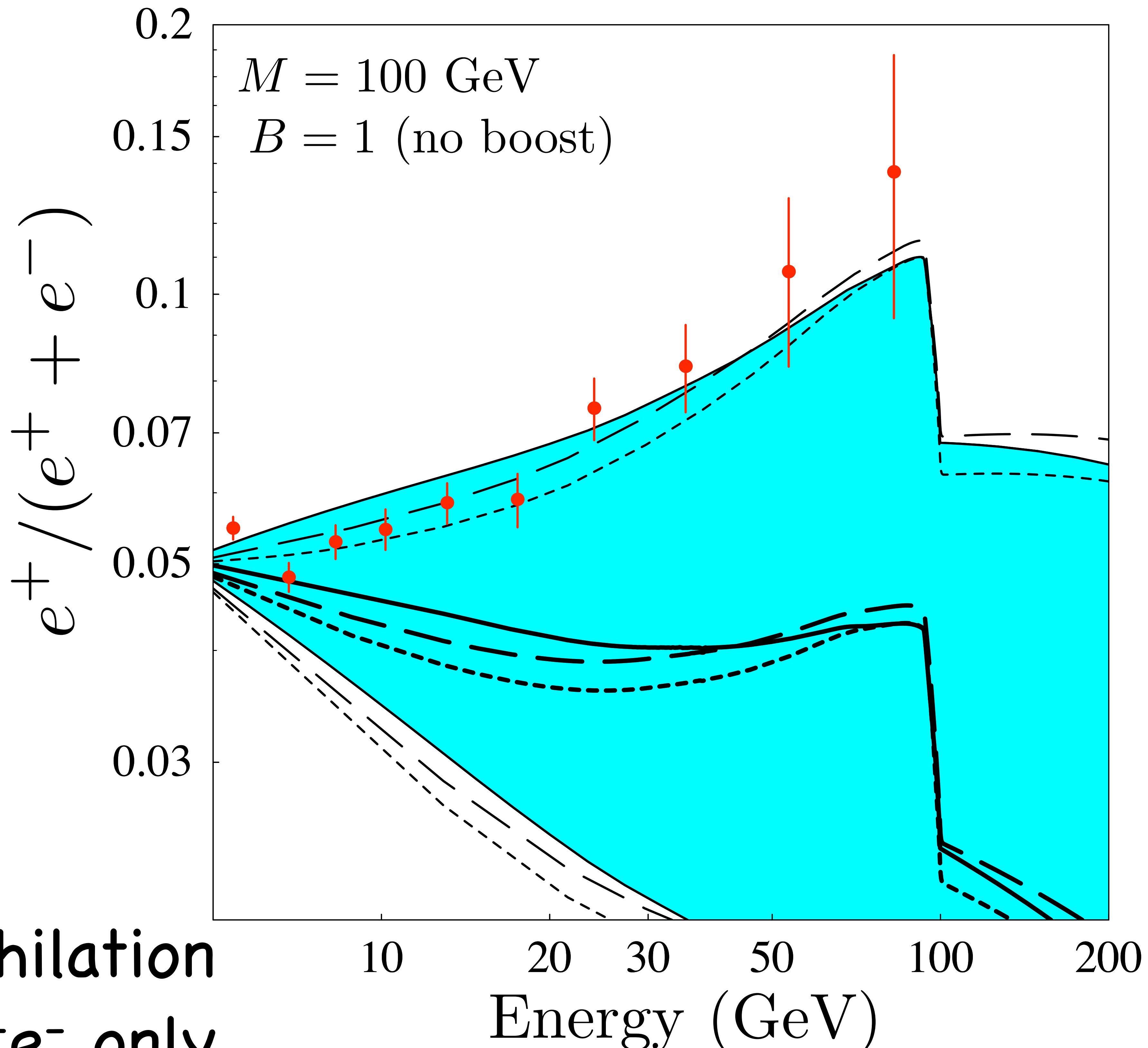
Ratio derived from:

- e^- data
- e^+ predicted secondary

(Hard to explain as electron deficit)

Harnik, GK

Dirac Dark Matter Prediction



Annihilation to e^+e^- only

Harnik, GK

Dirac Dark Matter:

BOOST = 1 for

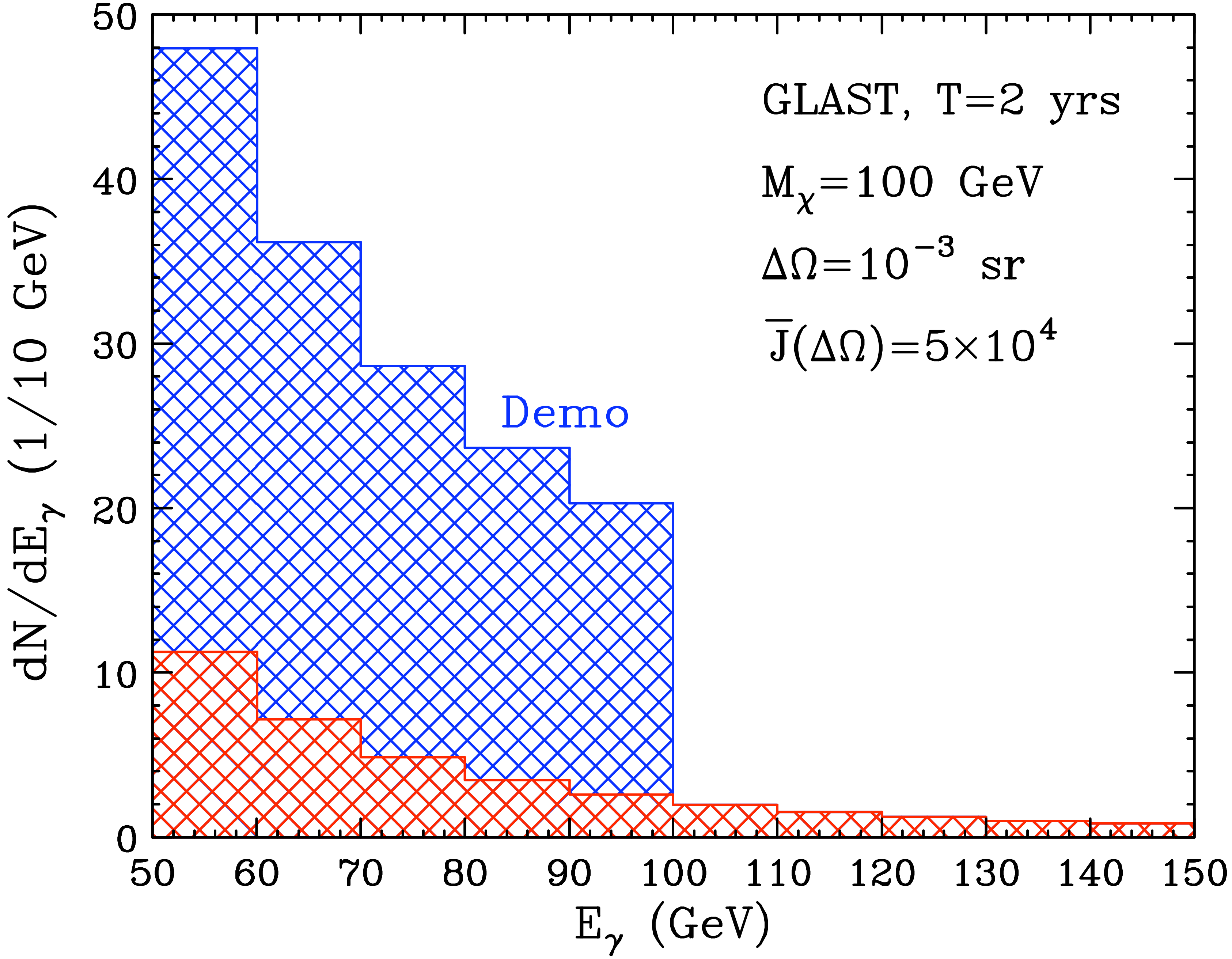
$M = 100$ GeV
$\Phi \approx E^{-3.5}$;
$\rho_{local} = 0.3$ GeV/cm^3

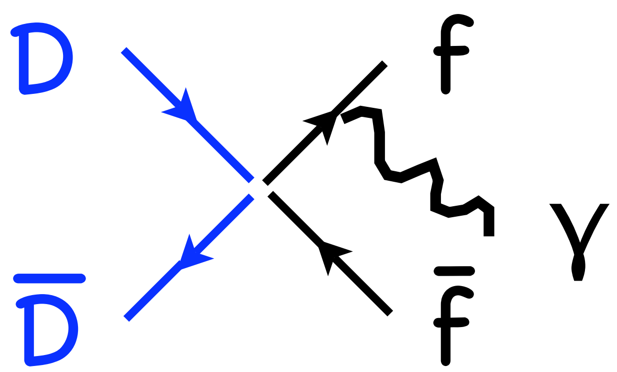
BOOST = 5 for

$M = 100$ GeV
$\Phi \approx E^{-3.15}$;
$\rho_{local} = 0.3$ GeV/cm^3

BOOST α M^2

Fermi/GLAST feature: FSR radiation





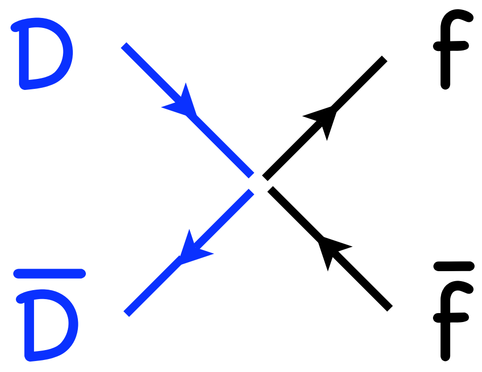
Size of signal?

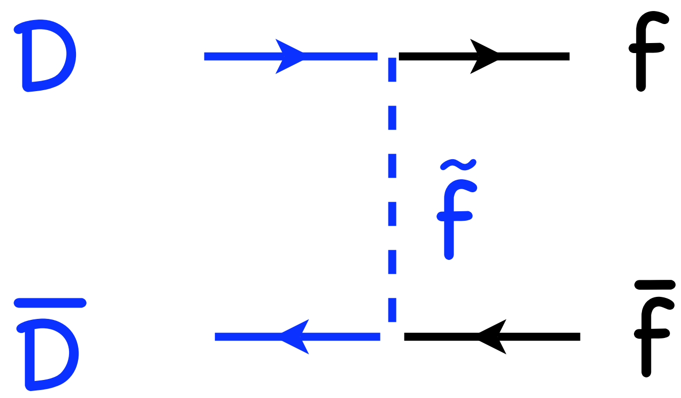
Birkedal, Mathev, Perelstein, Spray, hep-ph/0507194

Dirac Bino as Dirac Dark Matter

Interpretation of D as a (pure) Dirac Bino

Resolve the 4-fermion vertex as

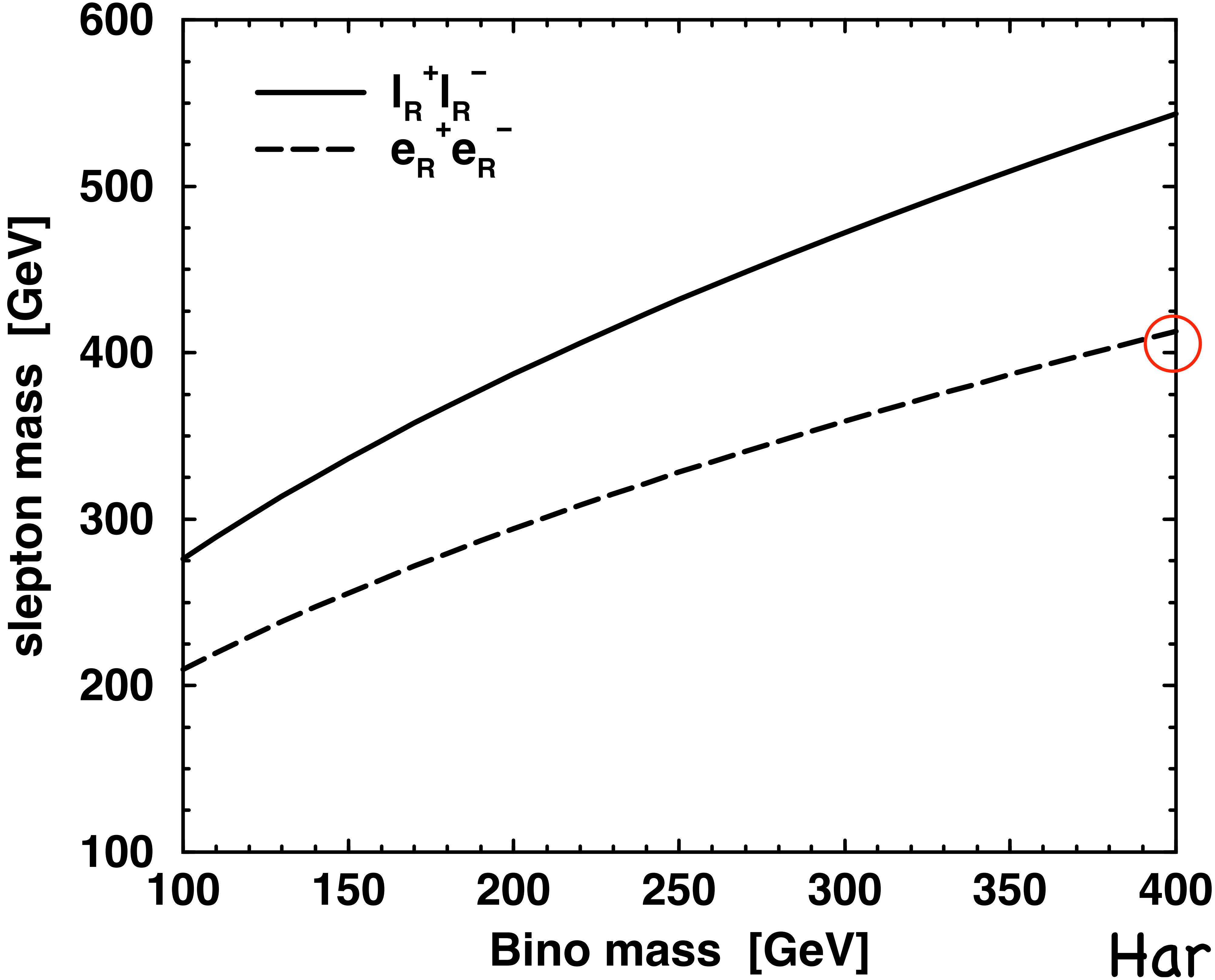




The dominance of leptonic annihilation results automatically given $Y_{eR}=1$ and some mild hierarchy, $m_{\tilde{l}} < m_{\tilde{q}}$

(and, dim-5 Higgs operator is absent)

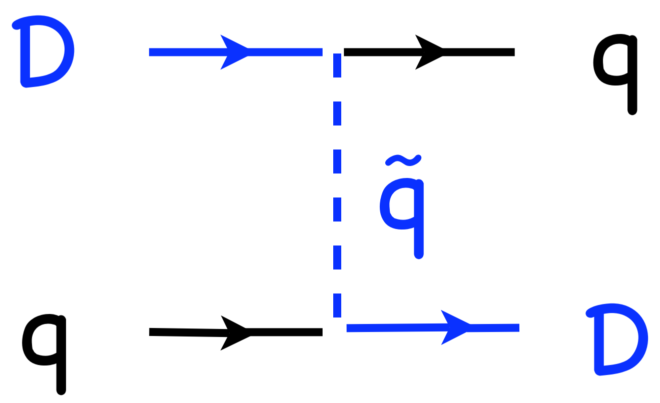
Matching thermal relic abundance, i.e., <σv> = 1 pb



Harnik, GK

Absence of Antiproton Excess + Direct Detection Bounds

Imply



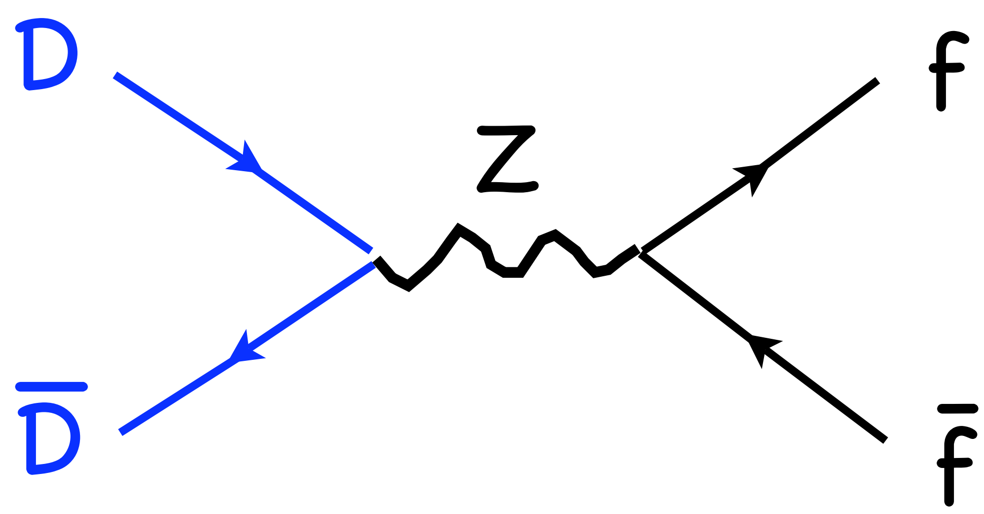
cannot be large.

Rough estimates of direct detection bounds suggest

$$m_{\tilde{q}} > 1.5 \text{ TeV}$$

for first generation, right-handed squarks.

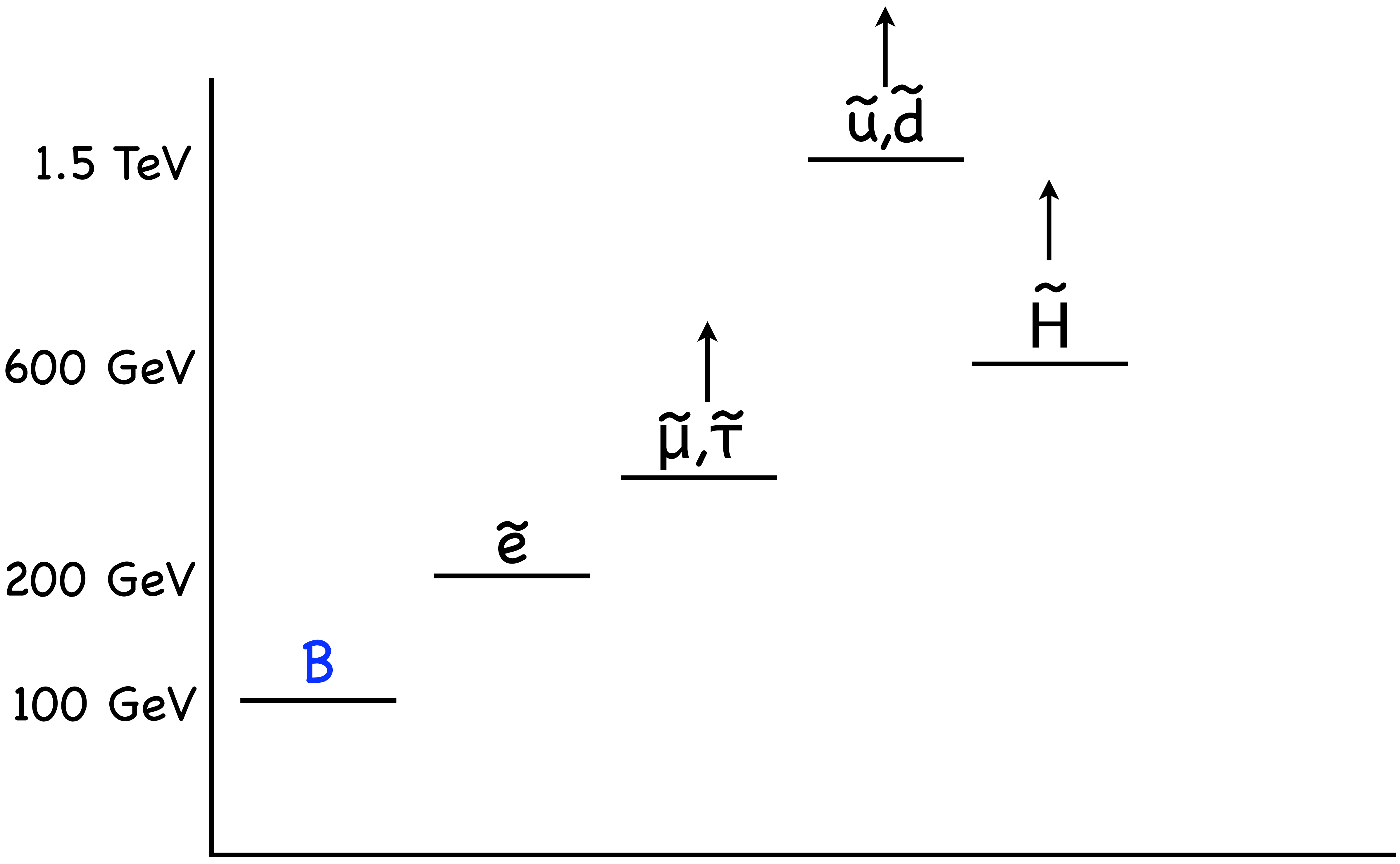
Also constraint on Higgsino content of LSP from direct detection



Our estimate, from $(g'v)^2/\mu^2 < 0.01$,

$\mu > 600$ GeV

To explain PAMELA...



Dirac Bino

Is an intriging prediction of R-symmetric supersymmetric models (Poppitz, Weiner, GK)

These models have very interesting flavor properties; Bino lighter than selectron, different from smuon/stau suggests observable LFV (work in progress)

Understanding how supergravity could exactly conserve a visible sector R-symmetry remains a puzzle...

Summary: Dark Matter

- Remarkable dark matter detection experiments underway; already strong constraints and hints towards the particle nature of DM

- One DM-DM-l-l operator can:
  - thermally produce $\Omega h^2 \approx 0.1$ relic abundance
  - automatically avoid direct detection
  - explain PAMELA ratio with minimal boost factor

- Collider implications of "unusual" dark matter candidates is ripe for exploitation

Summary: Dirac DM Features

For M < 250 GeV; sharp feature in positron ratio.

Fermi/GLAST FSR photon feature (robust?)

Do not need Sommerfeld enhancement (et al) to explain PAMELA with order (few) boost factor, nor decay into light scalar/gauge boson to get electron channel to dominate

Effective theory provides most straightforward way to test/reject/cross-test hypotheses.